CHAPTER 5

FORCE

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Objectives

The major goals of this chapter are to enable you to:

1. Relate force and the law of inertia.
2. Apply the law of acceleration.
3. Identify components of friction.
4. Analyze forces in one dimension.
5. Distinguish among weight, mass, and gravity.
6. Analyze how the law of action and reaction is used.

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Classical physics is sometimes called Newtonian physics in honor of Sir Isaac Newton, who lived from 1642 to 1727 and formulated three laws of motion that summarize much of the behavior of moving bodies.

Forces may cause motion. Inertia tends to resist the influence of an applied force. Forces, inertia, friction, and how they relate to motion are considered now.

5.1 Force and the Law of Inertia

As discussed in the previous chapter, if an object changes its velocity, we say it accelerates. But what causes an object to accelerate? Let's take an example of a soccer ball at rest on a field. What must you do to accelerate the ball? Similarly, if your car is approaching a red stoplight, what must you do to make the car accelerate to rest? The answer in both instances is to apply a force.

A **force** is any push or pull. Forces tend to either change the motion of an object or prevent the object from changing its motion. Force is a vector quantity and therefore has both magnitude and direction. The force tends to produce acceleration in the direction of its application. Therefore, if you want to accelerate the soccer ball, you need to kick it in the direction you want the ball to move. To get the car to slow down, you apply the brakes, which creates a force in the opposite direction of the car's motion and causes a negative acceleration.

Isaac Newton (1642–1727),

physicist, mathematician, and astronomer, was born in England. He is credited with discovering the laws of motion and gravitation, studying the nature of light and finding that white light is a mixture of colors that can be separated by refraction, inventing the calculus, and devising the first reflecting telescope. The metric unit of force, the newton, is named after him.

Not all forces result in acceleration. For example, if you attempt to push a large crate, it may not move because another force, in this case a frictional force, matches your pushing force, preventing you from moving it (Fig. 5.1). This concept of concurrent forces will be covered in Chapter 7.

The units for measuring force are the newton (N) in the metric system and the pound (lb) in the U.S. system. The conversion factor is

$$4.45\ \text{N} = 1\ \text{lb}$$

Let's examine the relationship between forces and motion. There are three relationships or laws that were discovered by **Isaac Newton** during the late seventeenth century. The three laws are often called Newton's laws. The first law, called the **law of inertia**, is as follows:

LAW OF INERTIA: NEWTON'S FIRST LAW

A body that is in motion continues in motion with the same velocity (at constant speed and in a straight line) and a body at rest continues at rest unless an unbalanced (outside) force acts upon it.

If an automobile is stopped (at rest) on level ground, it resists being moved. That is, a person is required to exert a tremendous push to get it moving. Similarly, if an automobile is moving—even slowly—it takes a large force to stop it. This property of resisting a change in motion is called inertia. **Inertia** is the property of a body that causes it to remain at rest if it is at rest or to continue moving with a constant velocity unless an unbalanced force acts upon it. When the accelerating force of an automobile engine is no longer applied to a moving car, the car will slow down. This is not a violation of the law of inertia because there are forces being applied to the car through air resistance, friction in the bearings, and the rolling resistance of the tires [Fig. 5.2(a)]. If these forces could be removed, the auto would continue moving with a constant velocity. Anyone who has tried to stop quickly on ice knows the effect of the law of inertia when frictional forces are small [Fig. 5.2(b)].

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Figure 5.1 The pushing force and the frictional force cancel each other out, resulting in zero acceleration.

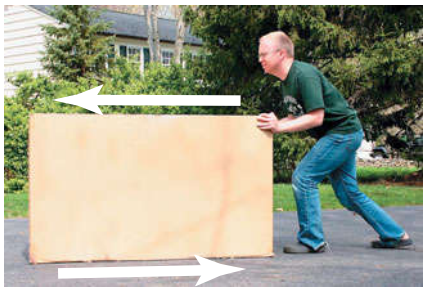
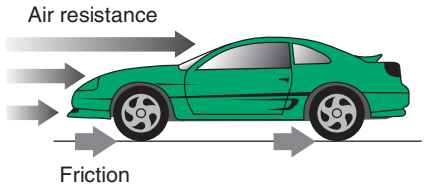
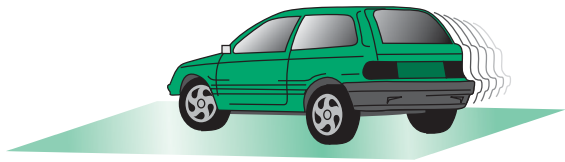


Figure 5.2



(a) Air resistance and friction slow the car.



(b) Inertia makes it hard to stop a car on ice.

The engine of a train makes use of the concept of inertia in incrementally starting a train that has far too much inertia to start moving all at once. The train is set in motion one car at a time. The couplers are loosely connected, which allows each car to start moving separately from the others. Then the inertia of each moving car aids in getting the rest of the cars moving. With use of this technique trains up to 1 mi long can be set in motion.

TRY THIS ACTIVITY

Inertia Tricks

Place a card on top of a glass. Then place a quarter on top of the card as in Fig. 5.3(a). Quickly flick the card horizontally. The inertia of the coin tends to keep it at rest horizontally. The force that causes the coin to move is the vertical force of gravity, which pulls it straight down into the glass as in Fig. 5.3(b).

Figure 5.3 When the card is flicked, the inertia of the quarter keeps it at rest until it falls into the glass.

(a) (b)

How could you remove a tablecloth from under a set of dishes without removing the dishes from the table? The trick to keeping the dishes on the table is to use a very smooth tablecloth without any hem and very quickly jerk the tablecloth backward in a slightly downward direction. We suggest that you practice with heavy objects on plastic plates. Remember that the more mass placed on the plates, the greater is the inertia.

Some objects more than others tend to resist changes in their motion. It is much easier to push a small automobile than to push a large truck into motion (Fig. 5.4). **Mass** *is a measure of the inertia of a body*, that is, a measure of the resistance a body has to changing its motion. The common units of mass are the kilogram (kg) in the metric system and the slug in the U.S. system. The conversion factor is 1 kg = 0.0685 slug.

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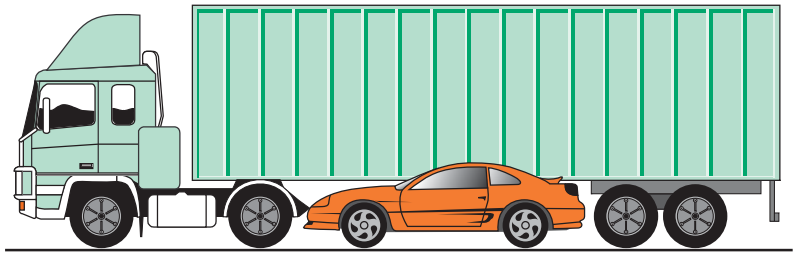
Figure 5.4 A larger body (in mass) has a greater resistance to a change in its motion than does a smaller one.



5.2 Force and the Law of Acceleration

The second law of motion, called the **law of acceleration**, relates the applied force, the mass, and the acceleration of an object.

LAW OF ACCELERATION: NEWTON'S SECOND LAW

The total force acting on a body is equal to the mass of the body times its acceleration.

In equation form this law is

$$F = ma$$

where F = total force
m = mass
a = acceleration

The formula states that when a force is applied to an object, the force causes the object to accelerate. The stronger the force, the larger is the acceleration. The weaker the force, the smaller is the acceleration. In addition, when pushed with the same force, a more massive object will accelerate less and a less massive object will accelerate more.

If the mass is kept constant,

$$F \sim a \qquad \text{(The force is directly proportional to the acceleration.)}$$

If the force is kept constant,

$$m \sim 1/a \qquad \text{(The mass is inversely proportional to the acceleration.)}$$

In SI units, the mass unit is the kilogram (kg) and the acceleration unit is metre/second/second (m/s^2). The force required to accelerate 1 kg of mass at a rate of 1 m/s^2 is

$$\begin{aligned} F &= ma \\ &= (1\text{ kg})(1\text{ m/s}^2) \\ &= 1\text{ kg m/s}^2 \end{aligned}$$

The SI force unit is the newton (N), named in honor of Isaac Newton, and is defined as

$$1\text{ N} = 1\text{ kg m/s}^2$$

In the U.S. system, the mass unit is the slug and the acceleration unit is foot/second/second (ft/s^2). The force required to accelerate 1 slug of mass at the rate of 1 ft/s^2 is

$$\begin{aligned} F &= ma \\ &= (1\text{ slug})(1\text{ ft/s}^2) \\ &= 1\text{ slug ft/s}^2 \end{aligned}$$

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The U.S. force unit is the pound (lb) and is defined as

$$1 \text{ lb} = 1 \text{ slug ft/s}^2$$

Note: The other metric unit of force is the dyne. One dyne is the force required to accelerate 1 g of mass at the rate of 1 cm/s^2. The dyne is not an SI unit, and its use is less common.

EXAMPLE 1

What force is necessary to produce an acceleration of 6.00 m/s^2 on a mass of 5.00 kg?

Data:

$$m = 5.00 \text{ kg}$$
$$a = 6.00 \text{ m/s}^2$$
$$F = ?$$

Basic Equation:

$$F = ma$$

Working Equation: Same

Substitution:

$$F = (5.00 \text{ kg})(6.00 \text{ m/s}^2)$$
$$= 30.0 \text{ kg m/s}^2$$
$$= 30.0 \text{ N} \qquad (1 \text{ N} = 1 \text{ kg m/s}^2)$$

EXAMPLE 2

What force is necessary to produce an acceleration of 2.00 ft/s^2 on a mass of 3.00 slugs?

Data:

$$m = 3.00 \text{ slugs}$$
$$a = 2.00 \text{ ft/s}^2$$
$$F = ?$$

Basic Equation:

$$F = ma$$

Working Equation: Same

Substitution:

$$F = (3.00 \text{ slugs})(2.00 \text{ ft/s}^2)$$
$$= 6.00 \text{ slug ft/s}^2$$
$$= 6.00 \text{ lb} \qquad (1 \text{ lb} = 1 \text{ slug ft/s}^2)$$

EXAMPLE 3

Find the acceleration produced by a force of $500\overline{0}$ N applied to a mass of 20.0 kg.

Data:

$$F = 500\overline{0} \text{ N}$$
$$m = 20.0 \text{ kg}$$
$$a = ?$$

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Basic Equation:

$$F = ma$$

Working Equation:

$$a = \frac{F}{m}$$

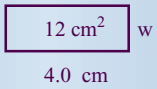
Substitution:

$$\begin{aligned} a &= \frac{500\ \text{N}}{20.0\ \text{kg}} \\ &= 25.0\frac{\text{N}}{\text{kg}} \\ &= 25.0\frac{\cancel{\text{N}}}{\cancel{\text{kg}}} \times \frac{1\ \cancel{\text{kg}}\ \text{m/s}^2}{1\ \cancel{\text{N}}} \\ &= 25.0\ \text{m/s}^2 \end{aligned}$$

Note: We use a conversion factor to obtain acceleration units.

PROBLEM SOLVING

SKETCH



DATA

$A = 12\ \text{cm}^2$, $l = 4.0$ cm, $w = ?$

BASIC EQUATION

$A = lw$

WORKING EQUATION

$$w = \frac{A}{l}$$

SUBSTITUTION

$$w = \frac{12\ \text{cm}^2}{4.0\ \text{cm}} = 3.0\ \text{cm}$$

PROBLEMS 5.2

Find the total force necessary to give each mass the given acceleration.

1. $m = 15.0$ kg, $a = 2.00$ m/s^2
2. $m = 4.00$ kg, $a = 0.500$ m/s^2
3. $m = 111$ slugs, $a = 6.70$ ft/s^2
4. $m = 91.0$ kg, $a = 6.00$ m/s^2
5. $m = 28.0$ slugs, $a = 9.00$ ft/s^2
6. $m = 42.0$ kg, $a = 3.00$ m/s^2
7. $m = 59.0$ kg, $a = 3.90$ m/s^2
8. $m = 2.20$ slugs, $a = 1.53$ ft/s^2

Find the acceleration of each mass with the given total force.

9. $m = 190$ kg, $F = 7600$ N
10. $m = 7.00$ slugs, $F = 12.0$ lb
11. $m = 3.60$ kg, $F = 42.0$ N
12. $m = 0.790$ kg, $F = 13.0$ N
13. $m = 110$ kg, $F = 57.0$ N
14. $m = 84.0$ kg, $F = 33.0$ N
15. $m = 9.97$ slugs, $F = 13.9$ lb
16. $m = 210$ kg, $F = 41.0$ N
17. Find the total force necessary to give an automobile of mass 1750 kg an acceleration of 3.00 m/s^2.
18. Find the acceleration produced by a total force of 93.0 N on a mass of 6.00 kg.
19. Find the total force necessary to give an automobile of mass 120 slugs an acceleration of 11.0 ft/s^2.
20. Find the total force necessary to give a rocket of mass 25,000 slugs an acceleration of 28.0 ft/s^2.
21. A forklift has a mass of 975 kg. What force must be applied to give it an acceleration of 2.50 m/s^2?
22. A power wheelbarrow has a mass of 432 kg. What force must be applied to give it an acceleration of 1.75 m/s^2?
23. What is the rate of deceleration of a 1400-kg SUV that is going 75.0 km/h and then slows to 25.0 km/h in 8.20 s?
24. An earthmover slows from 15.0 km/h to 3.00 km/h in 2.70 s. What is its rate of deceleration?
25. Find the total force necessary to give a 140 kg mass an acceleration of 41.0 m/s^2.
26. Find the acceleration produced by a total force of 300 N on a mass of 0.750 kg.
27. Find the mass of an object with acceleration 15.0 m/s^2 when an unbalanced force of 90.0 N acts on it.

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28. An automobile has a mass of $10\overline{0}$ slugs. The passengers it carries have a mass of 5.00 slugs each. (a) Find the acceleration of the auto and one passenger if the total force acting on them is $15\overline{0}0$ lb. (b) Find the acceleration of the auto and six passengers if the total force is again $15\overline{0}0$ lb.
29. Find the acceleration produced by a force of 6.75×10^6 N on a rocket of mass 5.27×10^5 kg.
30. An astronaut has a mass of 80.0 kg. His space suit has a mass of 15.5 kg. Find the acceleration of the astronaut during his space walk when his backpack propulsion unit applies a force to him (and his suit) of 85.0 N.
31. A discus thrower exerts a force of $14\overline{0}$ N on the discus. (a) If the discus has an acceleration of 19.0 m/s^2, what is the mass of the discus? (b) If the mass of the discus is doubled and the applied force remains the same, what is the new acceleration? (c) If the force is doubled and the mass is unchanged, how is the acceleration affected?
32. A scooter and rider together have a mass of 275 kg. (a) If the scooter slows with an acceleration of -4.50 m/s^2, what is the net force on the scooter and rider? (b) Describe the direction of the force and state the meaning of the $(-)$ sign.
33. A pickup truck with mass of 1230 kg moving at 105 km/h stops within a distance of 53.0 m. (a) What is the direction and size of the force that acts on the truck? (b) How much more slowing force would be required to stop the truck in half the distance?

5.3 Gravity and Weight

The **weight** of an object is the amount of *gravitational pull* exerted on an object by the earth. If this force is not balanced by other forces, an acceleration is produced. When you hold a brick in your hand as in Fig. 5.5, you exert an upward force on the brick that balances the downward force (weight). If you remove your hand, the brick moves downward due to the unbalanced force. The velocity of the falling brick increases, but the acceleration (rate of change of the velocity) is constant.

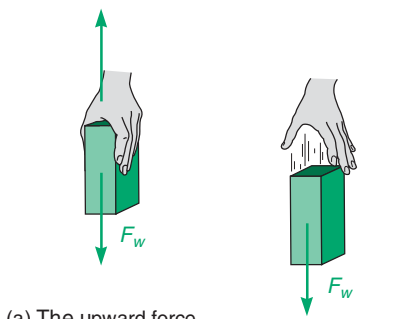
The acceleration of all objects near the surface of the earth is the same if air resistance is ignored. We call this acceleration due to the gravitational pull of the earth g. Its value is 9.80 m/s^2 in the metric system and 32.2 ft/s^2 in the U.S. system.

The *weight* of an object is the force exerted by the earth (or by another large body) and gives the object an acceleration g. This force can be found using $F = ma$, where $a = g$. If we abbreviate weight by F_w, the equation for weight is

$$F_w = mg$$

where F_w = weight
m = mass
g = acceleration due to gravity
g = 9.80 m/s^2 (earth, metric)
g = 32.2 ft/s^2 (earth, U.S.)

Figure 5.5 Balancing gravity in holding a brick.



(a) The upward force of the hand equals the downward force of the weight.

(b) The downward force of the weight is now greater.

EXAMPLE 1

Find the weight of 5.00 kg.

Data:

m = 5.00 kg
g = 9.80 m/s^2
F_w = ?

Basic Equation:

$$F_w = mg$$

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Working Equation: Same

Substitution:

$$F_w = (5.00 \text{ kg})(9.80 \text{ m/s}^2)$$
$$= 49.0 \text{ kg m/s}^2$$
$$= 49.0 \text{ N} \qquad (1 \text{ N} = 1 \text{ kg m/s}^2)$$

EXAMPLE 2

Find the weight of 12.0 slugs.

Data:

$$m = 12.0 \text{ slugs}$$
$$g = 32.2 \text{ ft/s}^2$$
$$F_w = ?$$

Basic Equation:

$$F_w = mg$$

Working Equation: Same

Substitution:

$$F_w = (12.0 \text{ slugs})(32.2 \text{ ft/s}^2)$$
$$= 386 \text{ slug ft/s}^2$$
$$= 386 \text{ lb} \qquad (1 \text{ lb} = 1 \text{ slug ft/s}^2)$$

Weight Versus Normal Force

When an object is in contact with a surface, a force is exerted on that object by the surface. This force, called a **normal force,** *is perpendicular to the contact surface.*

Picture a brick at rest on a table (Fig. 5.6) Since the brick is at rest, the contact force, pointing directly up from the table, must be equal to the magnitude of the brick's weight. If additional bricks are stacked on top of the original brick, the total weight of the bricks will increase, causing the normal force from the table to increase as well. Eventually, the table will not be able to support more and more bricks with enough of a normal force. When this occurs, the table will break, causing the bricks to accelerate down toward the ground.

Normal forces are an essential component of understanding how to calculate frictional forces, as disscussed in Section 5.4.

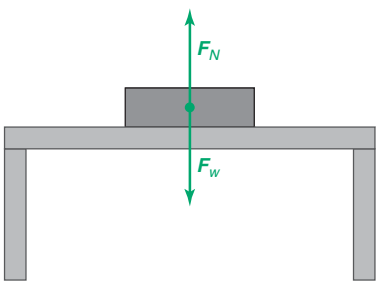

Figure 5.6 Since the brick is at rest, the normal force is equal in magnitude but opposite in direction to the weight of the brick.

Mass Versus Weight

Note that the mass of an object remains the same, but its weight varies according to the gravitational pull. For example, an astronaut of mass 75.0 kg has a weight of

$$F_w = mg = (75.0 \text{ kg})(9.80 \text{ m/s}^2) = 735 \text{ N}$$

on the earth. If that astronaut lands on the moon, where the acceleration due to gravity is less than it is on the earth, the astronaut will still have the same 75.0 kg mass but will weigh significantly less than 735 N. (The moon has less acceleration due to gravity than

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the earth in part because the moon is less massive than the earth. A full explanation will be given in Chapter 11.) The following example shows the astronaut's weight on the moon.

EXAMPLE 3

Find the 75.0-kg astronaut's weight on the moon, where $g = 1.63\ \text{m/s}^2$.

Data:

$$m = 75.0\ \text{kg}$$
$$g = 1.63\ \text{m/s}^2\ \text{(on moon)}$$
$$F_w = ?$$

Basic Equation:

$$F_w = mg$$

Working Equation: Same

Substitution:

$$F_w = (75.0\ \text{kg})(1.63\ \text{m/s}^2)$$
$$= 122\ \text{N} \qquad (1\ \text{N} = 1\ \text{kg m/s}^2)$$

Note that the astronaut's *mass* on the moon remains 75.0 kg.

Mass Versus Volume

Do not confuse mass and volume. The volume of an object is the measure of the space it occupies. Volume is measured in cubic units such as cm^3, ft^3, or L. The mass of an object is the amount of inertia or the amount of material it contains. The more mass contained in an object, the greater its inertia and the more force it takes to move it or change its motion. Compare the masses of two boxes of identical size, one filled with books and one empty. The box filled with books has more mass and requires more force to move it.

As an astronaut goes from the earth to the moon, his or her weight changes but mass and volume remain the same. Weight and mass are directly proportional in a given place, as we saw earlier.

PROBLEMS 5.3

Find the weight for each mass.

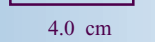
1. $m = 30.0\ \text{kg}$
2. $m = 60.0\ \text{kg}$
3. $m = 10.0\ \text{slugs}$
4. $m = 9.00\ \text{kg}$

Find the mass for each weight.

5. $F_w = 17.0\ \text{N}$
6. $F_w = 21.0\ \text{lb}$
7. $F_w = 12{,}000\ \text{N}$
8. $F_w = 25{,}000\ \text{N}$
9. $F_w = 6.7 \times 10^{12}\ \text{N}$
10. $F_w = 5.5 \times 10^{6}\ \text{lb}$
11. Find the weight of an 1150-kg automobile.
12. Find the weight of an 81.5-slug automobile.
13. Find the mass of a 2750-lb automobile.
14. What is the mass of a 20,000-N truck?
15. What is the mass of a 7500-N trailer?
16. Find the mass of an 11,500-N automobile.
17. Find the weight of a 1350-kg automobile (a) on the earth and (b) on the moon.
18. Maria weighs 115 lb on the earth. What are her (a) mass and (b) weight on the moon?

PROBLEM SOLVING

SKETCH



DATA

$A = 12\ \text{cm}^2$, $l = 4.0\ \text{cm}$, $w = ?$

BASIC EQUATION

$A = lw$

WORKING EQUATION

$$w = \frac{A}{l}$$

SUBSTITUTION

$$w = \frac{12\ \text{cm}^2}{4.0\ \text{cm}} = 3.0\ \text{cm}$$

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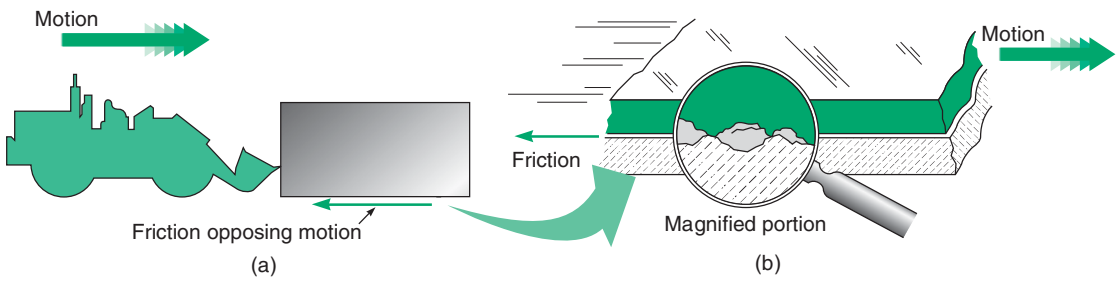
19. John's mass is 65.0 kg on the earth. What are his (a) mass and (b) weight on the moon?
20. What is your weight in newtons and in pounds?
21. What is your mass in kilograms and in slugs?
22. What are your U.S. mass and weight on the moon?
23. What are your metric mass and weight on the moon?
24. John's mass is 65.0 kg on the earth. What are his U.S. (a) mass and (b) weight 4000 mi above the surface of the earth, where $g = 7.85$ ft/s^2?
25. Maria weighs 115 lb on the earth. What are her U.S. (a) mass and (b) weight on Jupiter, where $g = 85.0$ ft/s^2?
26. John's mass is 65.0 kg on the earth. What are his metric (a) mass and (b) weight on Mars, where $g = 3.72$ m/s^2?
27. What are your metric mass and weight on Jupiter, where $g = 25.9$ m/s^2?
28. What are your metric mass and weight on Mars, where $g = 3.72$ m/s^2?
29. An automobile transmission weighs 995 N. What is its mass?
30. A power wheelbarrow weighs 210 N. What is its mass?

5.4 Friction

Friction is a force that resists the relative motion of two objects in contact caused by the irregularities of the two surfaces sliding or rolling across each other, which tend to catch on each other (Fig. 5.7). In general, it is found that if two rough surfaces are polished, the frictional force between them is lessened. However, there is a point beyond which this decrease in friction is not observed. If two objects are polished such that the surfaces are very smooth, then the frictional force actually increases. (Two panes of glass provide an example.) This is related to the fact that friction can also be caused by the adhesion of molecules of one surface to the molecules of the other surface. This adhesive force is similar to the electric forces that hold atoms together in solids.

Figure 5.7 Friction resists motion of objects in contact with each other.



Static friction is the force that opposes the start of the relative motion of two objects in contact with each other. It is sometimes called starting friction. Once the touching objects are in motion relative to each other, the friction is generally less and is called *kinetic friction* or sliding friction.

Friction is both a necessity and a hindrance in our everyday lives. Without friction, walking, driving, swimming and many other normal activities would not be possible. Experiments with frictional forces indicate the following general characteristics:

1. ***Friction is a force that always acts parallel to the surface in contact and opposite to the direction of motion.*** If there is no motion, friction acts in the direction opposite any force that tends to produce motion [Fig. 5.8(a)]. The resistance to motion is the frictional force.

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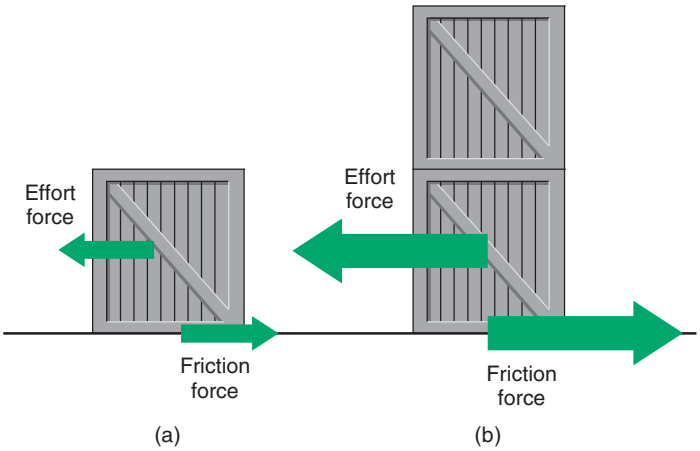
Figure 5.8 Friction increases as the force between the surfaces increases.



2. ***Static friction is greater than kinetic friction.*** When you push a large box across the floor, you probably notice that it takes more force to start it moving than to keep it moving. This is due to inertia. A box at rest tends to remain at rest, whereas a moving box tends to continue moving. Pushing someone on a sled is a good way to experience the difference between static and kinetic friction.
3. ***Friction increases as the force between the surfaces increases.*** It is much easier to slide a light crate than a heavy one across the floor [Fig. 5.8(b)]. *The area of contact is not relevant.* Friction depends only on the nature of the materials in contact and the force pressing them together.

The characteristics of friction can be described by the following equation:

$$F_f = \mu F_N$$

where F_f = frictional force
F_N = normal force (force perpendicular to the contact surface)
μ = coefficient of friction

The **coefficient of friction** is the ratio between the frictional force and the normal force of the object. The coefficient describes how rough or smooth the two surfaces are when they are in contact with each other. A higher coefficient of friction indicates two rough surfaces, whereas a lower number indicates two smooth surfaces.

Representative values for the coefficients of friction for some surfaces are given in Table 5.1. Values may vary with surface conditions.

Table 5.1 Coefficients of Friction (μ)

Material	Static Friction	Kinetic Friction
Steel on steel	0.58	0.20
Steel on steel (lubricated)	0.13	0.13
Glass on glass	0.95	0.40
Hardwood on hardwood	0.40	0.25
Steel on concrete		0.30
Aluminum on aluminum	1.9	
Rubber on dry concrete	2.0	1.0
Rubber on wet concrete	1.5	0.97
Aluminum on wet snow	0.4	0.02
Steel on Teflon	0.04	0.04

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TRY THIS ACTIVITY

How to Find μ

Establish your own chart of coefficients of friction for various pairs of surfaces. Take any fairly massive object, perhaps a textbook, and measure its normal force by weighing it with a spring scale. (We will be doing this activity only on horizontal surfaces so the normal force is the same as the weight of the object.) To determine the coefficient of friction between the two surfaces, slowly pull horizontally on the spring scale until the object moves at a constant velocity. As the object moves, the reading on the scale gives the applied pulling force, which is also the force of friction. Record your data in a table and compare. The rougher materials should have a larger coefficient of friction than the smoother materials.

In general:

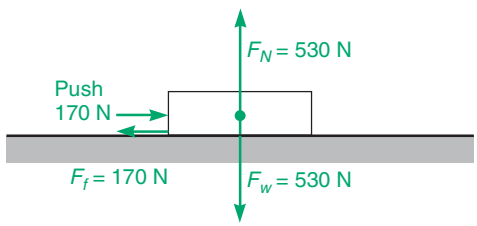
To reduce kinetic friction:

1. Use smoother surfaces.
2. Use lubrication to provide a thin film between surfaces.
3. Use Teflon to greatly reduce friction between surfaces when an oil lubricant is not desirable, such as in electric motors.
4. Substitute rolling friction for sliding friction. Rolling friction is the resistance that occurs when an object, such as a wheel or a tire, rolls on a surface. It is usually much smaller than sliding friction. Using ball bearings and roller bearings greatly reduces friction.

EXAMPLE 1

A force of 170 N is needed to keep a 530-N wooden box sliding on a wooden floor. What is the coefficient of kinetic friction?

Sketch:



Data:

$$F_f = 170 \text{ N}$$
$$F_N = 530 \text{ N}$$
$$\mu = ?$$

Basic Equation:

$$F_f = \mu F_N$$

Working Equation:

$$\mu = \frac{F_f}{F_N}$$

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Substitution:

$$\mu = \frac{170 \cancel{\text{N}}}{530 \cancel{\text{N}}}$$
$$= 0.32$$

Note that μ does not have a unit because the force units always cancel.

PHYSICS CONNECTIONS

Friction and Antilock Brakes

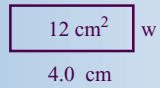
Since the invention of the automobile, engineers have worked to design brakes that reduce the stopping distance for automobiles. The most impressive advance in automobile braking technology is the antilock braking system (ABS). ABS technology is found on most new automobiles and works to prevent changing the friction between the tires and the road to sliding or kinetic friction. The ratio of the coefficients of static friction to kinetic friction of rubber on dry cement is 2.0 to 1.0.

Automobiles stop by using friction to slow down during normal braking situations. This friction takes place while the tires are in contact with the pavement. Locking the wheels or braking on ice or a film of water can quickly change static friction between the road and the tires to kinetic friction between the tires and the road. Sliding tires cause cars to go out of control and result in longer stopping distances.

Antilock braking systems use computerized sensors to monitor the rotational speed of the tires while braking. If the sensors detect a sudden decrease in the turning speed of the tires (indicating a skid), the control unit repeatedly releases and then restores the pressure to the brakes at a rate of up to 15 times per second. In essence, the ABS pulses the brakes on and off to keep the tires from sliding. Maintaining the static frictional force throughout braking keeps the car in control and reduces its stopping distance.

PROBLEMSOLVING

SKETCH



DATA

$A = 12\ \text{cm}^2$, $l = 4.0$ cm, $w = ?$

BASIC EQUATION

$A = lw$

WORKING EQUATION

$$w = \frac{A}{l}$$

SUBSTITUTION

$$w = \frac{12\ \text{cm}^2}{4.0\ \text{cm}} = 3.0\ \text{cm}$$

PROBLEMS 5.4

1. A cart on wheels weighs 2400 N. The coefficient of rolling friction between the wheels and floor is 0.16. What force is needed to keep the cart rolling uniformly?
2. A wooden crate weighs 780 lb. What force is needed to start the crate sliding on a wooden floor when the coefficient of static friction is 0.40?
3. A piano weighs 4700 N. What force is needed to start the piano rolling across the floor when the coefficient of static friction is 0.23?
4. A force of 850 N is needed to keep the piano in Problem 3 rolling uniformly. What is the coefficient of rolling friction?
5. A dog sled weighing 750 lb is pulled over level snow at a uniform speed by a dog team exerting a force of 60 lb. Find the coefficient of friction.
6. A horizontal conveyor belt system has a coefficient of kinetic friction of 0.65. The motor driving the system can deliver a maximum force of 2.5×10^6 N. What maximum total weight can be placed on the conveyor system?
7. A tow truck can deliver 2500 lb of pulling force. What is the maximum-weight truck that can be pulled by the tow truck if the coefficient of rolling friction of the truck is 0.10?
8. A snowmobile is pulling a large sled across a snow-covered field. The weight of the sled is 3560 N. If the coefficient of friction of the sled is 0.12, what is the pulling force supplied by the snowmobile?
9. An automobile weighs 12,000 N and has a coefficient of static friction of 0.13. What force is required to start the auto rolling?
10. A light truck weighs 14,000 N with a coefficient of static friction of 0.140. What force is required to start the truck rolling?
11. A stake truck weighs 20,000 N with a coefficient of static friction of 0.130. What force is required to start the truck rolling?

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12. If the coefficient of rolling friction of the auto in Problem 11 is 0.080, what force is required to keep it moving once it is in motion?
13. An alloy block is placed on a smooth composite table. If a force of 14.0 N is required to keep the 40.0-N block moving at a constant velocity, what is the coefficient of kinetic friction for the table and block?
14. If a 20.0-N casting is placed on the block in Problem 13, what force is necessary to keep the block and casting moving at constant velocity?
15. Rubber tires and wet blacktop have a coefficient of kinetic friction of 0.500. A pickup truck with mass 750 kg traveling 30.0 m/s skids to a stop. (a) What is the size and direction of the frictional force that the road exerts on the truck? (b) Find the acceleration of the truck. (c) How far would the truck travel before coming to rest?
16. The coefficient of friction in Problem 15 is 0.700 if the tires do not skid. (a) Would the force of friction be greater than, less than, or equal to that in Problem 15? (b) Would the truck in (a) stop in a shorter, a longer, or an equal distance compared to the truck in Problem 15?

5.5 Total Forces in One Dimension

In the examples used to illustrate the law of acceleration, we discussed only total forces. We need to remember that forces are vectors and have magnitude and direction. The total force acting on an object is the resultant of the separate forces.

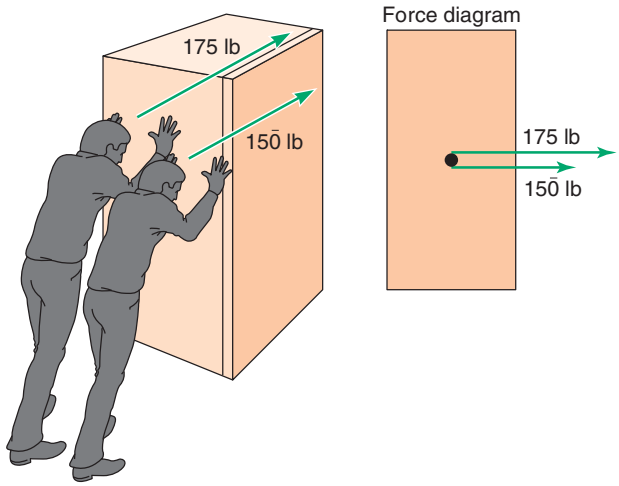
When forces act in the same or opposite directions (in one dimension), the total, or net, force can be found by adding the forces that act in one direction and subtracting the forces that act in the opposite direction.

It is often useful to draw the forces as vectors.

EXAMPLE 1

Two workers push in the same direction (to the right) on a crate. The force exerted by one worker is 150 lb. The force exerted by the other is 175 lb. Find the net force exerted.

Sketch:



Both forces act in the same direction, so the total force is the sum of the two.

Note: The Greek letter Σ (sigma) means "sum of."

$$\Sigma \mathbf{F} = 175 \text{ lb} + 150 \text{ lb}$$
$$= 325 \text{ lb to the right}$$

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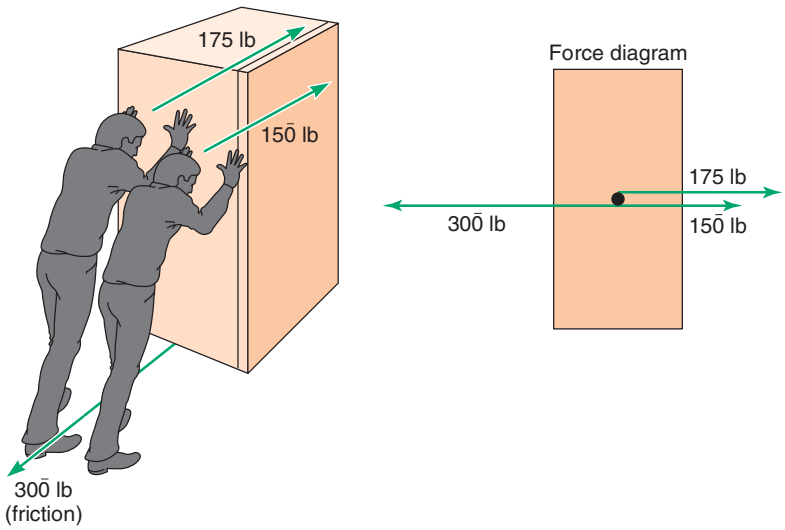
EXAMPLE 2

The same two workers push the crate to the right, and the motion is opposed by a static frictional force of 300 lb. Find the net force.

Sketch:



The workers push in one direction and static friction pushes in the opposite direction, so we add the forces exerted by the workers and subtract the frictional force.

$$\begin{aligned}\Sigma\mathbf{F} &= 175\text{ lb} + 150\text{ lb} - 300\text{ lb} \\ &= 25\text{ lb to the right}\end{aligned}$$

EXAMPLE 3

The crate in Example 2 has a mass of 5.00 slugs. What is its acceleration when the workers are pushing against the frictional force?

Data:

$$\begin{aligned}F &= 25\text{ lb (from Example 2)} \\ m &= 5.00\text{ slugs} \\ a &= ?\end{aligned}$$

Basic Equation:

$$F = ma$$

Working Equation:

$$a = \frac{F}{m}$$

Substitution:

$$\begin{aligned}a &= \frac{25\text{ lb}}{5.00\text{ slugs}} \\ &= 5.0\,\frac{\cancel{\text{lb}}}{\cancel{\text{slugs}}} \times \frac{1\ \cancel{\text{slug}}\ \text{ft/s}^2}{1\ \cancel{\text{lb}}} \\ &= 5.0\text{ ft/s}^2\end{aligned}$$

Note: We use a conversion factor to obtain acceleration units.

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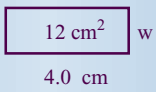
EXAMPLE 4

Two workers push in the same direction on a large pallet. The force exerted by one worker is 645 N. The force exerted by the other worker is 755 N. The motion is opposed by a frictional force of 1175 N. Find the net force.

$$\Sigma \mathbf{F} = 645\ \text{N} + 755\ \text{N} - 1175\ \text{N}$$
$$= 225\ \text{N}$$

PROBLEM SOLVING

SKETCH



DATA

$A = 12\ \text{cm}^2$, $l = 4.0\ \text{cm}$, $w = ?$

BASIC EQUATION

$A = lw$

WORKING EQUATION

$$w = \frac{A}{l}$$

SUBSTITUTION

$$w = \frac{12\ \text{cm}^2}{4.0\ \text{cm}} = 3.0\ \text{cm}$$

PROBLEMS 5.5

Find the net force including its direction when each force acts in the direction indicated.

1. 17.0 N to the left, 20.0 N to the right.
2. 265 N to the left, 85 N to the right.
3. 100.0 N to the left, 75.0 N to the right, and 10.0 N to the right.
4. 190 lb to the left, 87 lb to the right, and 49 lb to the right.
5. 346 N to the right, 247 N to the left, and 103 N to the left.
6. 37 N to the right, 24 N to the left, 65 N to the right, and 85 N to the right.
7. Find the acceleration of an automobile of mass 100 slugs acted upon by a driving force of 500 lb that is opposed by a frictional force of 100 lb (Fig. 5.9).
8. Find the acceleration of an automobile of mass 1500 kg acted upon by a driving force of 2200 N that is opposed by a frictional force of 450 N.
9. A truck of mass 13,100 kg is acted upon by a driving force of 8900 N. The motion is opposed by a frictional force of 2230 N. Find the acceleration.
10. A speedboat of mass 30.0 slugs has a 300-lb force applied by the propellers. The friction of the water on the hull is a force of 100 lb. Find the acceleration.
11. A truck with a mass of 14,000 kg is pushed with a force of 9200 N. If the frictional force is 2150 N, what is the truck's acceleration?
12. A trailer has a mass of 5000 kg. It is pulled by a truck with a force of 8750 N. If the frictional force is 2000 N, what is its acceleration?
13. A refrigeration unit on a job site must be slid into place. If the frictional force of 975 N opposes the motion and two workers apply a total force of 1095 N to the unit, what is the net force on the unit?
14. A light truck of 2000 kg mass has to be pushed with a force of 1975 N. If the frictional force is 550 N, what is its acceleration?

Figure 5.9

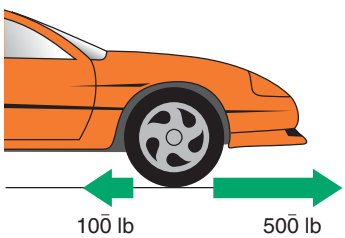
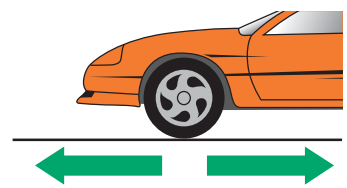


Figure 5.10 The ground supplies the force to accelerate the car.



$\mathbf{F}_1 = -\mathbf{F}_2$

5.6 Law of Action and Reaction

When an automobile accelerates, we know that a force is being applied to it. What applies this force? You may think that the tires exert this force on the auto. This is not correct because the tires move along with the auto and there must be a force applied to them also. The ground below the tires actually supplies the force that accelerates the car (Fig. 5.10). This force is called a *reaction* to the force exerted by the tires on the ground, which is called the *action force*. The third law of motion, the **law of action and reaction**, can be stated as follows:

LAW OF ACTION AND REACTION: NEWTON'S THIRD LAW

For every force applied by object *A* to object *B* (action), there is an equal but opposite force exerted by object *B* to object *A* (reaction).

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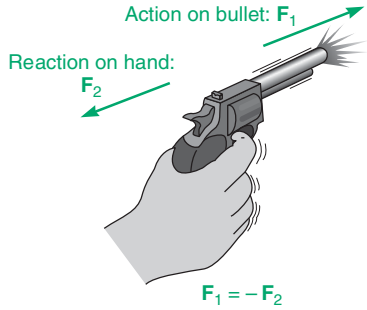
When a bullet is fired from a handgun (action), the recoil felt is the reaction. These forces are shown in Fig. 5.11. Note that the action and reaction forces *never* act on the same object.

For every interaction, the forces always occur in pairs and are equal and opposite. When you sit on a chair, your weight pushes *down* on the chair; the chair pushes *up* with a force equal to your weight. If the chair pushed up with a force less than your weight, you would fall through it. If the chair pushed up with a force greater than your weight, you would be pushed up above the seat.

Most interactions depend on force. What would happen if you were standing in a small boat and tried to jump across to the nearby boat dock? You would fall into the water. Why? The force you would exert against the boat as you jumped would push it away, and the equal and opposite force the boat would exert on you would not result in much forward motion for you.

Figure 5.11 The magnitude of the reaction force always equals the magnitude of the action force.



TRY THIS ACTIVITY

Balloon Rocket

Blow up a balloon and release it. What causes the balloon to accelerate? What causes it to stop accelerating? Use Newton's third law of motion to describe how the balloon accelerates forward.

Figure 5.12 A balloon rocket

To create a straight path for the balloon, tape the balloon to a straw that is on a string that serves as a guide wire between two points or people, as shown in Fig. 5.12.

PHYSICS CONNECTIONS

Shuttle Launch

Newton's second and third laws of motion play a vital role during the launch of the Space Shuttle. (See Fig. 5.13.) Just as a massive gun recoils as a less-massive bullet is fired, the massive shuttle recoils or "lifts off" as the less-massive, high-velocity gaseous exhaust is ejected from the rocket engines.

In order to overcome the force of gravity that the earth applies to all objects, the Space Shuttle must carry enough fuel in its external tank and solid rocket boosters to overcome the gravitational pull of the earth. To do so, the shuttle carries more than 4.4 million pounds of rocket fuel for use during its launch. Compare this to the weight of the Space Shuttle itself, which is 170,000 pounds, and it is clear that the shuttle uses a tremendous amount of fuel to lift off.

In order to take advantage of Newton's third law and send the shuttle into space, the gaseous exhaust from the burned fuel is ejected from the shuttle's rocket boosters at speeds of nearly 6000 mi/h. As the rocket fuel is burned and its gaseous exhaust is ejected out of the rocket, the overall weight of the shuttle's fuel decreases. According to Newton's second law, if the same force is applied but the mass is reduced, the acceleration increases.

Figure 5.13 The gas particles are expelled at a high velocity, causing the shuttle to recoil or launch into space.

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Glossary

Coefficient of Friction The ratio between the frictional force and the normal force of an object. The number represents how rough or smooth two surfaces are when moving across one another. (p. 135)

Force A push or a pull that tends to change the motion of an object or prevent an object from changing motion. Force is a vector quantity and thus has both magnitude and direction. (p. 126)

Friction A force that resists the relative motion of two objects in contact caused by the irregularities of two surfaces sliding or rolling across each other. (p. 134)

Inertia The property of a body that causes it to remain at rest if it is at rest or to continue moving with a constant velocity unless an unbalanced force acts upon it. (p. 126)

Law of Acceleration The total force acting on a body is equal to the mass of the body times its acceleration. (Newton's second law). (p. 128)

Law of Action and Reaction For every force applied by object *A* to object *B* (action), there is an equal but opposite force exerted by object *B* on object *A* (reaction). (Newton's third law). (p. 140)

Law of Inertia A body that is in motion continues in motion with the same velocity (at constant speed and in a straight line) and a body at rest continues at rest unless an unbalanced (outside) force acts upon it (Newton's first law). (p. 126)

Mass A measure of the inertia of a body. (p. 127)

Normal Force Force perpendicular to the contact surface. (p. 132)

Weight The amount of gravitational pull exerted on an object by the earth or by another large body. (p. 131)

Formulas

5.2 $F = ma$

5.3 $F_w = mg$

where $g = 9.80 \text{ m/s}^2$ (metric)
$g = 32.2 \text{ ft/s}^2$ (U.S.)

5.4 $F_f = \mu F_N$

Review Questions

1. Force
   (a) is a vector quantity. (b) may be different from weight.
   (c) does not always cause motion. (d) all of the above.
2. The metric weight of a 10-lb bag of sugar is approximately
   (a) 4.45 N. (b) 44.5 N. (c) 445 N. (d) none of the above.
3. Mass and weight
   (a) are the same. (b) are different. (c) do not change wherever you are.
4. According to Newton's second law, the law of acceleration,
   (a) acceleration is equal to mass times force.
   (b) mass is equal to mass times acceleration.
   (c) force is equal to mass times acceleration.
   (d) none of the above.
5. Friction
   (a) always acts parallel to the surface of contact and opposite to the direction of motion.

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(b) acts in the direction of motion.
(c) is smaller when starting than when moving.
(d) is an imaginary force.

6. Cite three examples of forces acting without motion being produced.
7. (a) Does a pound of feathers have more inertia than a pound of lead?
   (b) Does the pound of feathers have more mass than the pound of lead?
8. How is inertia a factor in multicar pileups?
9. Using your own words, state Newton's first law, the law of inertia.
10. Distinguish between velocity and acceleration.
11. When the same force is applied to two different masses, which will have a greater acceleration?
12. Is 3 pounds heavier than 10 newtons?
13. Explain how life would be easier or more difficult without friction.
14. Explain how the weight of an astronaut is different on the moon than on the earth. Would the astronaut's mass be different?
15. Explain the difference between action and reaction forces.
16. State Newton's third law of motion, the law of action and reaction, in your own words.

Review Problems

1. A crate of mass 6.00 kg is moved by a force of 18.0 N. What is its acceleration?
2. An 825-N force is required to pedal a bike with an acceleration of 11.0 m/s^2. What is the mass of the bike and person?
3. A block of mass 0.89 slug moves with a force of 17.0 lb. Find the block's acceleration.
4. What is the force necessary for a 2400-kg truck to accelerate at a rate of 8.0 m/s^2?
5. Two movers push a piano across a frictionless surface. One pushes with 29.0 N of force and the other mover exerts 35.0 N. What is the total force?
6. A 340-N box has a frictional force of 57 N. Find the coefficient of kinetic friction.
7. A truck pulls a trailer with a frictional force of 870 N and a coefficient of friction of 0.23. What is the trailer's normal force?
8. A steel box is slid along a steel surface. It has a normal force of 57 N. What is the frictional force?
9. A rock of a mass 13.0 kg is dropped from a cliff. Find its weight.
10. A projectile has a mass of 0.37 slug. Find its weight.
11. What force is required to produce an acceleration of 4.00 m/s^2 on a wrecking ball with a mass of 50.0 kg?
12. Find the total force necessary to give a 280-kg motorcycle an acceleration of 3.20 m/s^2.
13. A force of 175 N is needed to keep a 640-N stationary engine on wooden skids from sliding on a wooden floor. What is the coefficient of static friction?
14. A crated garden tractor weighs 375 N. What force is needed to start the crate sliding on a wooden floor when the coefficient of static friction is 0.40?
15. Find the acceleration of a forklift of mass 1400 kg pushed by a force of 2100 N that is opposed by a frictional force of 425 N.
16. What is the weight of a 375-kg air compressor?
17. What is the mass of a 405-N welder?
18. What is the mass of a 12.0-N hammer?

PROBLEMSOLVING

SKETCH

$12\ cm^2$ | w

4.0 cm

DATA

$A = 12\ cm^2$, $l = 4.0$ cm, $w = ?$

BASIC EQUATION

$A = lw$

WORKING EQUATION

$$w = \frac{A}{l}$$

SUBSTITUTION

$$w = \frac{12\ cm^2}{4.0\ cm} = 3.0\ cm$$

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APPLIED CONCEPTS

1. Engineers at Boeing developing specs for their "next-generation" 737 aircraft needed to know the acceleration of the 737-900 during a typical take-off. (a) What acceleration would they calculate given the plane's 78,200-kg mass and its maximum engine force of 121,000 N? (b) How fast would the plane be traveling after the first 500 m of runway? (c) How fast would it travel after the first 1500 m of runway?

2. The Apollo spacecrafts were launched toward the moon using the Saturn rocket, the most powerful rocket available. Each rocket had five engines producing a total of 33.4×10^6 N of force to launch the 2.77×10^6-kg spacecraft toward the moon. (a) Find the average acceleration of the spacecraft. (b) Calculate the altitude of the rocket 2.50 min after launch—the point when the spacecraft loses its first stage.

3. Kirsten's mass is 3.73 slugs. Being the physics fan that she is, she decides to see what her apparent weight will be during an elevator ride. Beginning at rest, the elevator accelerates upward at 4.50 ft/s^2 for 3.00 s and then continues at a constant upward velocity. Finally, as the elevator comes to a stop at the top floor, the elevator slows down (accelerates downward but continues to move upward) at a rate of -5.5 ft/s^2 (the negative sign represents the downward direction). Find Kirsten's weight while the elevator is (a) at rest. (b) speeding up. (c) moving at a constant velocity. (d) slowing down. The next time you ride in an elevator, concentrate on when you feel heavier and when you feel lighter.

4. A motorcycle racer traveling at 145 km/h loses control in a corner of the track and slides across the concrete surface. The combined mass of the rider and bike is 243 kg. The steel of the motorcycle rubs against the concrete road surface. (a) What is the frictional force between the road and the motorcycle and rider? (b) What would be the acceleration of the motorcycle and rider during the wipeout? (c) Assuming there were no barriers to stop the motorcycle and rider, how long would it take the bike and the rider to slow to a stop?

5. The motorcycle and rider are sliding with the same acceleration as found in Problem 4. If the motorcycle and rider have been sliding for 4.55 s, what will be the force applied to the motorcycle and the rider when they strike the side barrier and come to rest in another 0.530 s?

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